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INVESTIGATION OF FAULT DETECTION AND ANALYSIS METHODS FOR CENTRAL MAINTENANCE SYSTEMS

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Abstract. Modern airplanes have a large number of interconnected avionic systems that need an accurate and confident real-time fault detection/isolation (FDI) monitor in central maintenance systems (CMS) for possible malfunctions or abnormalities. Model-based diagnosis, which compares predicted behaviour with actual behaviour, is used for efficient analysis of maintenance data for FDI. This paper investigates the different types of model-based fault detection/isolation approaches according to type of aircraft. The importance of real-time (in-flight) diagnosis is discussed.

Keywords: fault detection and isolation, model-based diagnosis, real-time diagnosis, central maintenance system.

1. Introduction

Having an overall look at aircraft systems or analyzing a system to locate a faulty component started to be very difficult when avionic systems became more complicated and interrelated. This complexity increased the workload for flight crews and maintenance personnel for diagnosing faults.

It is essential to locate the root cause of a fault while many other interconnected subsystems may also give fault indications that may possibly hide the root cause. Therefore aircraft computers use diagnostic approaches that collect data from sensors and computers to analyze for fault diagnosis.

Presently, nearly all-diagnostic approaches for engineering systems are based on *model-based diagnosis* relying on practical experiences in the past (Console, Dreiser 1999). According to the completeness of the model, model-based diagnosis can be applied by using adductive or deductive reasoning (Cheng *et al.* 2003, Peischl, Wotowa 2003). The adductive approach requires a faulty model to interpret the best explanation or the most probable root cause for a fault, while the deductive approach requires consistent observation and predictions (Poole 1989).

In real world, practical systems of aviation, faults may have behaviour that is dynamic and varies over time and that requires a proper approach to model the aircraft for good fault detection and isolation (Console 1997, Rahmani, Stone 1992).

Also, practical systems may suffer from the need of real-time diagnosis of multiple faults, which are quite likely to happen in an aircraft. Real-time diagnosis (in-flight) requires a model that adapts (changes) itself according to faults that occur and presents the most possible fault according to the new model (Jackson 1997). Another practical experience: dealing with multiple faults requires statistical methods that reduce the number of components those are possibly faulty (Arjunan 1998).

In a Boeing 777 airplane, the onboard diagnostics and maintenance system collects the necessary data for FDI by applying a model-based diagnostic model and records for future processes (Ramohalli 1992, Felke 1994).

The architecture of the aircraft avionics system determines the diagnostic approach by constituting a centralized or distributed structure such as Boeing versus Airbus.

2. Central maintenance

Since the very early analogue circuits, avionics have had a *built-in test* (BIT) that continuously monitors the system and has the capability to report a failure inside the system. The first CMS approach was only collecting BIT reports from individual avionics and presenting them in a central display to provide a general monitor for flight crews. As digital data buses were introduced, CMS started to receive continuous BIT reports and performed fault isolation (location) analysis to find out the root cause among reported faults. The new generation of systems is expected to detect a fault before its occurrence (prognostic) and provide corrective action. A central maintenance system, as described in the ARINC 624 standard, is simply illustrated in figure 1.

A central maintenance computer receives BIT reports and data from *Airplane Condition Management System* (ACMS) sensors and processes them with regard to its diagnostic database. The status of the aircraft can be seen on *Maintenance Access Terminal* (MAT) screens in the cockpit or on the portable MATs of technicians.

The basic tasks expected from a CMS are as follows:

- Identifying the root cause of the problem by tracing the observed effects.
- Preventing the problem from causing another function to fail.
- Generating advisory warnings to the cockpit.
- Keeping the necessary fault history and maintenance data for further analysis.

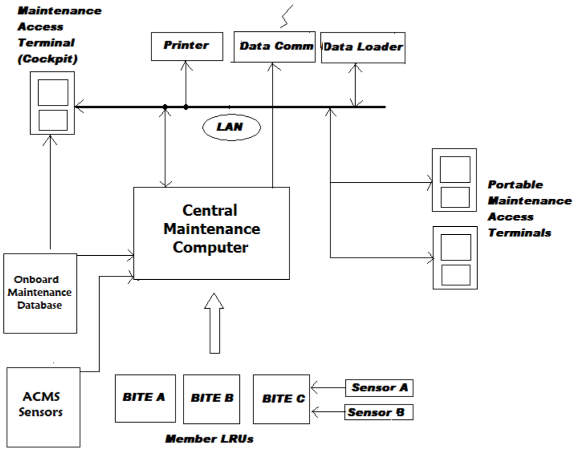

Fig. 1. Central maintenance system overview

3. Fault detection, isolation and identification

Avionics have a large number of interconnections that can allow the fault of a single component to propagate and cause the failure of other individual components. It is therefore essential to analyze the fault reports to find the root cause of the problem for proper corrective action or repair.

Fault detection refers to the indication that something in the system is wrong (without showing the cause). Fault detection is a must for practical engineering systems. Locating the root cause of a fault is called *fault isolation*, and it is essential for the diagnosis of practical systems. As a new approach, *fault identification* refers to determine the magnitude of the fault and whether it is necessary to take the proper corrective action for the fault. An example of detection, isolation and identification sequence is given in figure 2.

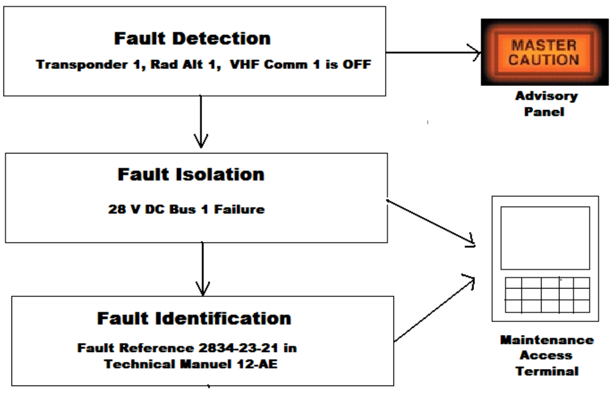

Fig. 2. Detection, isolation and identification for an assumed fault scenario

4. FDI methods

Model-free methods, such as *limit checking*, simply compare whether the observed value exceeds a predefined limit or uses special sensor that senses individual diagnostic data. However, diagnosis of a complicated system (such as an aircraft) requires a more complicated technique (Gertler 1998).

Model-based diagnosis compares the behaviour observed in the system with a predefined mathematical model of the system. The model-based approach has the advantage of containing the fault scenarios that can be matched with observations in order to conclude a diagnosis.

5. Model-based diagnosis

In this approach, the system is expected to work correctly according to a predicted behaviour. If a fault is detected with regard to predefined set of correct behaviour or faulty behaviour, then a search for the location of the fault is done with regard to predefined set of scenarios those can lead to the fault observed.

It depends on the completeness of the system to define the predicted behaviour according to faulty or correct behaviour. When the model is completely known, *deductive reasoning* is used to detect consistent fault scenarios that are already defined. On the other hand, *adductive reasoning* can still extract the most probable faults or the best explanations for an undefined symptom when the model of the system is not completely defined.

Example 1. Deductive Reasoning:

It is absolute that the sum of the internal angles of a triangle is 180°. This means that the third angle is 40° if the other two angles are 80° and 60°. In reference to figure 3a, the failure and effects can easily be defined for such a simplified system that only consists of a lamp and a switch. The deductive approach constitutes that if both the lamp and the switch are OK, and then there must be light. Then, the diagnosis can only be thus: If there is no light when the switch is on, either the lamp or the switch is faulty. However, it cannot evaluate other effects, which are shown in figure 3b, such as the battery is low or the cable is not conducting.

Example 2. Adductive Reasoning:

In reference to figure 3b, if there is a constraint such as the battery has 6 hours of energy and we have a sensor to measure it, a more probable diagnosis can be concluded: If the system clock has been operating for 3 hours, then the battery cannot be low and this leads to the diagnosis that the cable might not be conducting. It should be noted, however, that this is only the best explanation and not a certain diagnosis.

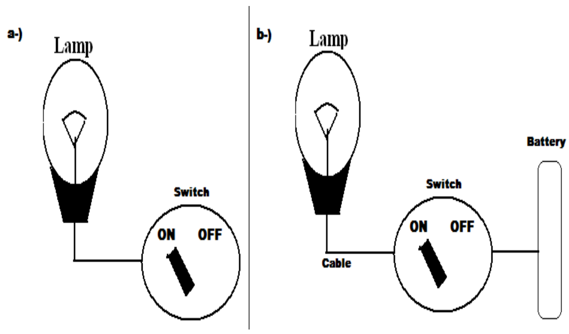

Fig. 3. Examples for a-) deductive and b-) adductive reasoning

6. Temporal diagnosis

Obviously, actual systems are generally variable over time and have temporal behaviour. *Time variance* refers to components having different types of faults over time and *temporal behaviour* refers to the effect of a fault after a period of time.

Example 3. Low Oil Pressure (Console 1997):

A low oil pressure warning in an aircraft can be generated for two reasons: oil loss (leakage) or oil consumption. The start of a low oil pressure warning should be at least 2 hours after the start of oil consumption. Also, oil consumption should be at least 2 hours long to cause low oil pressure. The formulation in LaTeR language is given in the following equation.

$$\begin{aligned} & oil\_loss(T_{ol}) \rightarrow low\_oil\_pressure(T_{lop}) \\ & Cons: \{T_{ol} \geq T_{lop}\} \\ & oil\_consumption(T_{oc}) \rightarrow low\_oil\_pressure(T_{lop}) \\ & Cons: \{T_{oc} \geq T_{lop}, T_{oc} > 2, T_{oc} - T_{lop} \geq 2\} \end{aligned} \qquad (1)$$

Consequently, temporal analysis can make the following diagnoses:

- If T_{lop} is less than 2 hours, low oil pressure cannot be due to oil consumption but might be due to oil loss.
- If T_{lop} is between 2 and 4 hours, low oil pressure might be due to either oil consumption or oil loss.
- If T_{lop} is more than 4 hours, low oil pressure is possibly due to oil consumption.

In temporal diagnosis, it is important to consider the necessities of storing the model current situation and using it when the effect of the fault is observed. This causes the need for large memory and the necessity to deal with large amount of data that need to be kept while waiting for the effect of the fault.

7. Multiple faults

The previous approaches considered that only one fault could happen in a defined time interval. Real systems (especially military aircraft) may suffer from multiple faults, however. *Multiple faults* refer to the faults that are not related to each other but have effects on the system in the same time interval.

Dealing with multiple faults requires numerous tests (sensors) that support the constraints to make a diagnosis. Statistical techniques are therefore applied to reduce the number of fault possibilities that need to be tested. Consequently, the diagnosis process is more efficient by saving memory and speed.

In a commercial airliner, it is not likely that two unrelated faults would occur at the same interval thanks to redundant systems. Military aircraft, however, may suffer from difficult flying conditions (hard landings, dust, over-speed, etc.) or anti-aircraft fire and might therefore have multiple faults (Fig. 4). Their CMS should respond/adapt the aircraft immediately.

Fig. 4. A-10 military aircraft hit by small-arms fire

8. Real-time diagnosis

Presently, aircraft diagnosis generally aims at producing a health status for maintenance purposes by collecting and analyzing large amount of data. Diagnosis can be very critical, however, in emergency situations during flight when multiple fault warnings are generated and immediate action is required for flight safety. The CMS should therefore generate corrective actions or provide advice concerning troubleshooting in order to help the flight crew take a decision.

In real-time model-based diagnosis, when a fault occurs, the system should save instance, adapt the model for a new situation (faulty), and evaluate the next fault according to the newly adapted model. Human intervention should be considered according to the task of the diagnosis, that is to say the complexity of advisory information that needs to be presented to the flight crew. The system should rank the possible faults according to the diagnosis.

9. Dependence on aircraft ideology

Even though both Boeing and Airbus produce aircraft with correspondent systems for almost the same purposes, their approaches to aircraft structure differ. The main difference between Boeing and Airbus structures is the use of data buses (except for Airbus A 380, which uses a centralized approach).

Boeing 777 uses centralized common multi-point ARINC 629 data buses, which are called systems buses (four) and flight control buses (three), and also a number of point-to-point ARINC 429 data buses (Fig. 5). The data collecting function is carried out by an *airplane information and management system* (AIMS) in which all avionics share the same sources such as power supply, I/O ports, processors, common software, etc.

In the Airbus approach (Fig. 6), systems are connected through point-to-point ARINC 429 data buses and with some analogue connections. This means that systems may have only a single connection with each other. Also, two central maintenance computers themselves perform the data collection function. Individual avionics have their own computerized components and sources.

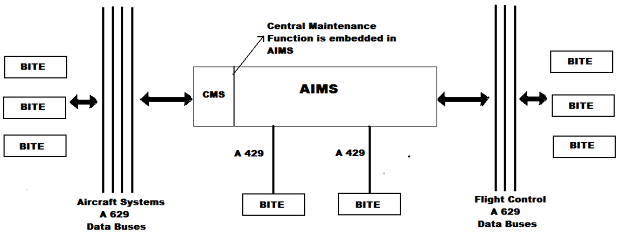

Fig. 5. Central maintenance system of Boeing 777

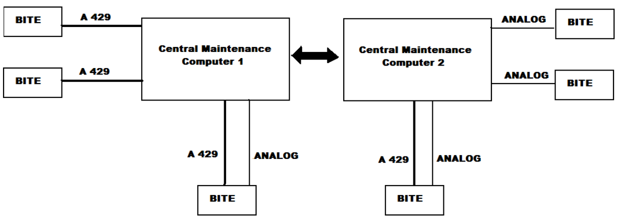

Fig. 6. Central maintenance system of Airbus A 330/340

The centralized approach of Boeing 777 AIMS eventually makes it easier to detect a fault since the common sources of avionics are assembled together. Multi-point ARINC 629 data buses provide flexibility in re-directing (by-passing) faulty lines after fault detection. In Airbus CMS, all avionics individually send their fault reports through a dedicated ARINC 429 line. This may increase the workload on FDI due to the high amount of data from different sources and the possibility of misconnections.

10. Conclusions

1. Model-based diagnosis can work efficiently if the structure size of the system is modelled according to the diagnostic task. A large model provides accuracy in diagnosis in maintenance thanks to many defined symptoms, but this causes a slow speed in real-time diagnosis due to the high number of symptoms those should be checked.
2. The temporal behaviour of faults should be considered carefully while modelling the system. A very dynamic model would be hard to design and maintain.
3. The occurrence of multiple and unrelated faults is important to consider for the model-based diagnosis of military aircraft.
4. The architecture of an aircraft avionics system (centralized or distributed) plays an important role in determining the diagnostic approach.

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